Determining the Magnetospheric Convection Electric Field from Lunar Shadowing: Past, Present, and Future

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PAST:

Apollo 15 & 16 Particles and Fields Subsatellites (PFS 1 & 2)

• First spacecraft to use **lunar shadowing** to determine the magnetospheric convection electric field [e.g., Anderson, 1970; Chase et al., 1974; McCoy et al., 1975; 1976; Lin et al., 1977]

• Measured **omni-directional** electron flux at 0.5, 2, 6, & 14 keV
• Orbit inclination: PFS 1: ~ 28°; PFS 2: ~ 10° (nearly equatorial)
  PFS 2: Apr. 1972 – May 1972
  (Total of 8 magnetotail passes)

**Summary of Results**

• Observed range of convection electric field, $E$: < 0.02 – 2 mV/m
  Median of ~ **0.15 mV/m** in the dawn-dusk direction
• Corresponding convection velocity, $V_D$: < 5 – 190 km/s
  Median of ~ **15 km/s** toward the neutral sheet
Ideal Omni-directional Flux Profiles

[Graphs showing omnidirectional flux profiles with labeled points A, B, C, D, D', D'', and E.]
Methodology

• In the high latitude magnetotail, solar wind electrons travel Earthward on open field lines

• The solid body of the Moon acts as a particle absorber creating a lunar shadow in the Earthward electron flux

• Electrons just outside the lunar shadow mirror near Earth and return to the vicinity of the Moon deflected by the magnetospheric cross tail convection electric field

• By measuring this displacement of mirrored electrons (the distance from B to C), the electric field can be determined

**Lunar shadowing** is the most sensitive technique to measure weak electric fields (< 0.1 mV/m) in the low-density magnetotail
PRESENT:

Lunar Prospector Electron Reflectometer (ER)

• Measured 3D electron distributions
• Energy range: ~10 eV – 20 keV (ΔE/E ~ 38%)
• Time resolution: 2.5 sec integration time; 80 sec cadence
• Angular resolution: up to 22.5° X 22.5° in equatorial bins
• Orbit inclination: 90° (polar orbit)
  (18 magnetotail passes – more than doubles the amount of data from PFS 1 & 2)

Increased energy, angular, and temporal resolutions of ER should allow us to determine the convection electric field from lunar shadowing with greater sensitivity and accuracy
Orbit Configuration

LP: 1998-04-11/02:00:00 - 08:00:00

Ideal Flux Profiles

Earthward Shadow (Solid Body)
Tailward Shadow $E_1$, $E_2$

Field-Aligned (Earthward) Flux

Anti-Aligned (Tailward) Flux
Panels 1 & 2: Magnetic field
Magnetic field magnitude is stable and magnetic field direction is Earthward → Northern lobe

Panels 3 – 6: Electron flux
Field-aligned (pitch angle ≤ 60°) & anti-aligned (pitch angle ≥ 120°) directional fluxes
• ≤ 500 eV: solar photon contamination in anti-aligned direction
• ≥ 2keV: low particle counts

Panels 7 & 8: LP orbit
Is LP magnetically connected to the Moon? |Polarity| = 1, yes; = 0, no
Does LP see the Sun? = 1, yes; = 0, no

3 lunar orbits (A to E) → 3 shadow events

For the following computations, only use 0.8 and 1.2 keV energy channels
Shadow 1: $\Delta t_{B-C}^{1.2 \, \text{keV}}: 1130 \pm 80 \, \text{s}$
$\Delta z_{B-C}^{1.2 \, \text{keV}}: 1260 \pm 130 \, \text{km}$

Shadow 2: $\Delta t_{B-C}^{1.2 \, \text{keV}}: 723 \pm 80 \, \text{s}$
$\Delta z_{B-C}^{1.2 \, \text{keV}}: 635 \pm 130 \, \text{km}$

Shadow 3: $\Delta t_{B-C}^{1.2 \, \text{keV}}: 858 \pm 80 \, \text{s}$
$\Delta z_{B-C}^{1.2 \, \text{keV}}: 945 \pm 130 \, \text{km}$
Shadow 1: $\Delta t_{B-C}^{0.8\text{ keV}}: 1372 \pm 80$ s  
$\Delta z_{B-C}^{0.8\text{ keV}}: 1646 \pm 130$ km

Shadow 2: $\Delta t_{B-C}^{0.8\text{ keV}}: 1286 \pm 80$ s  
$\Delta z_{B-C}^{0.8\text{ keV}}: 1426 \pm 130$ km

Shadow 3: $\Delta t_{B-C}^{0.8\text{ keV}}: 858 \pm 80$ s  
$\Delta z_{B-C}^{0.8\text{ keV}}: 945 \pm 130$ km
Results

The displacement, $Z$, is the product of the convection velocity, $V_D$, and the round-trip travel time of the mirrored electrons, $t_m$:

$$Z = V_D \cdot t_m = (E \times B)/B^2 \cdot t_m;$$

$$E = -(Z \times B)/t_m$$

where $t_m [s] = d/v_e \approx 120 R_E \cdot 6378 \text{ km}/R_E/(18800 \text{ km/s} \cdot \sqrt{E [\text{keV}]})$

(for a more rigorous treatment of $t_m$, see McCoy et al. [1975])

We assume $Z = \Delta z_{B-C}$; i.e., $V_D = -V_{DZ}$, and $E = E_Y$ (dawn-dusk)

→ lower limit of $E$

$E_1^{1.2 \text{ keV}} = 0.44 \pm 0.05 \text{ mV/m}$  \hspace{1cm} $E_1^{0.8 \text{ keV}} = 0.48 \pm 0.04 \text{ mV/m}$  \hspace{1cm} \text{consistent!}$

$E_2^{1.2 \text{ keV}} = 0.22 \pm 0.05 \text{ mV/m}$  \hspace{1cm} $E_2^{0.8 \text{ keV}} = 0.41 \pm 0.04 \text{ mV/m}$  \hspace{1cm} \text{inconsistent!}$

$E_3^{1.2 \text{ keV}} = 0.33 \pm 0.05 \text{ mV/m}$  \hspace{1cm} $E_3^{0.8 \text{ keV}} = 0.27 \pm 0.04 \text{ mV/m}$  \hspace{1cm} \text{consistent!}$
Solar Wind Conditions

- Wind was located about 225 $R_E$ upstream

- $B$, $V$, & $E$ time-shifted to 60 $R_E$ downtail

- $B_X$ mostly > 0

- $B_Y \sim E_Z$ mostly < 0

- $B_Z \sim -E_Y$ weak, variable but no more variable during 2nd shadow (inconsistent $E$) than during 3rd shadow (consistent $E$) (?)
FUTURE:

Future Work:

• Determine $E$ for 18 months of data
  • LP spent $\sim 1$ week/month in the magnetotail
  • $\sim \frac{1}{2}$ of that time in the lobe (other $\frac{1}{2}$ in the plasma sheet)
  • 2 hour orbital period
  $\rightarrow > 700$ orbits

• More rigorous determination of $t_m \rightarrow$ particle tracking
  Track particles using semi-empirical magnetic field model
  (e.g., T96 or your favorite model)

• Correlate with solar wind and IMF conditions
  How does solar wind influence $E$?
FUTURE (CONT’D):

Future Mission Planning:

• Address Problems with ER data
  • Need better solar photon rejection
  • Also need high geometric factor since density is low

• Increase sensitivity (reduce uncertainty)
  → Increase data sampling cadence
  Currently 80 s cadence → ± ~ 0.05 mV/m uncertainty

• Currently only measure component of \( \mathbf{V}_D \) parallel to orbit plane
  → \( \mathbf{E} \) perpendicular to orbit plane
  In order to completely constrain \( \mathbf{V}_D \) (hence, \( \mathbf{E} \), assuming \( E_{//} = 0 \)), requires **2 spacecraft**
Possible Future 2 Spacecraft Orbit Configuration

Earthward Shadow (Solid Body)
Tailward Shadow
$E_1$, $E_2$